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Implications of Uncertainty and Variability in the Life Cycle Assessment of Pig Production Systems

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Abstract

Goal, Scope and Background. Calculating LCA outcomes implies the use of parameters, models, choices and scenarios which introduce uncertainty, as they imperfectly account for the variability of both human and environmental systems. The analysis of the uncertainty of LCA results, and its reduction by an improved estimation of key parameters and through the improvement of the models used to convert emissions into regional impacts, such as eutrophication, are major issues for LCA.

Methods. In a case study of pig production systems, we propose a simple quantification of the uncertainty of LCA results (intra-system variability) and we explore the inter-system variability to produce more robust LCA outcomes. The quantification of the intra-system uncertainty takes into account the variability of the technical performance (crop yield, feed efficiency) and of emission factors (for NH_3, N_2O and NO_3) and the influence of the functional unit (FU) (kg of pig versus hectare used). For farming systems, the inter-system variability is investigated through differentiating the production mode (conventional, quality label, organic (OA)), and the farmer practices (Good Agricultural Practice (GAP) versus Over Fertilised (OF)), while for natural systems, variability due to physical and climatic characteristics of catchments expected to modify nitrate fate is explored.

Results and Conclusion. For the eutrophication and climate change impact categories, the uncertainty associated with field emissions contributes more to the overall uncertainty than the uncertainty associated with emissions from livestock buildings, with crop yield and with feed efficiency. For acidification, the uncertainty of emissions from livestock buildings is the single most important contributor to the overall uncertainty. The influence of the FU on eutrophication results is very important when comparing systems with different degrees of intensification such as GAP and OA. Concerning the inter-system variability, differences in farmer practices have a larger effect on eutrophication than differences between production modes. Finally, the physical characteristics of the catchment and the climate strongly affect the results for eutrophication. In conclusion, in this case study, the main sources of uncertainty are in the estimation of emission factors, due both to the variability of environmental conditions and to lack of knowledge (emissions of N_2O at the field level), but also in the model used for assessing regional impacts such as eutrophication.

Recommendation and Perspective. Suitable deterministic simulation models integrating the main controlling variables (environmental conditions, farmer practices, technology used) should be used to predict the emissions of a given system as well as their probabilistic distribution allowing the use of stochastic modelling. Finally, our simulations on eutrophication illustrate the necessity of integrating the fate of pollutants in models of impact assessment and highlight the important margin of improvement existing for the eutrophication impact assessment model.

Keywords: Eutrophication; fate factor; life cycle assessment (LCA); pig production; nitrate; site-dependency; uncertainties

Introduction

Pig production and especially its conventional mode on slatted floors, has a poor image with the general public due to its responsibility in the degradation of the environment. Alternative pig production systems such as straw litter systems or organic systems are preferred (Petit and van der Werf 2003). However, studies presenting the assessment of the impacts of both conventional and alternative pig production systems are scarce (Kumm 2002). This lack of global assessments of the impacts of pig production systems can be explained by the difficulty of assessing the complex relations between farming systems and environmental systems presenting both an important variability (Audsley et al. 1997, Mattsson 1999, Cowell and Clift 2000, Gosse et al. 2000, Brentrup 2003). LCA has been recognised as a valuable tool for assessing the environmental impacts of agricultural production (van der Werf and Petit 2002) and has been applied to a range of agricultural systems (Audsley et al. 1997, Blonk et al. 1997, Carlsson-Kanyama 1998, Cederberg and Mattsson 2000, Brentrup et al. 2001, Haas et al. 2001, Cederberg and Darelius 2002, Spies et al. 2002, de Boer 2003, Brentrup 2003). However, the uncertainty of LCA outcomes is a crucial issue for the credibility of this methodology (Huijbregts et al. 2001).

Uncertainty stems from a lack of knowledge concerning the real value of a quantity. Variability corresponds to the natural heterogeneity of the values. Calculating LCA outcomes implies the use of parameters, models, choices and scenarios which introduce uncertainty, as they imperfectly account for the variability of the real world (Huijbregts 1998a). Much research work has been conducted to clarify the concepts linked with uncertainty and to conceive tools for its quantification (Heijungs 1996, Weidema and Wesnaes 1996, Huijbregts 1998a and b, Heijungs and Kleijn 2001, Huijbregts et al. 2001, Björklund 2002, Heijungs and Huijbregts 2004). To quantify the uncertainty of LCA results, a sensitivity analysis can be used for each parameter separately (Audsley et al. 1997). Uncertainty analysis can also be conducted to quantify the aggregated uncertainty linked with the major input variables. Scenario analysis, statistical analysis (Heijungs 1996) and stochastic analysis are the main tools used to quantify the uncertainty of LCA results (Björklund 2002, Heijungs and Huijbregts 2004). Stochastic modelling is presented as the most promising of these, but it has essentially been applied for industrial or energy production (Kennedy

et al. 1996, Maurice et al. 2000, McCleese and LaPuma 2002, Huijbregts et al. 2003, Dones et al. 2005). For statistical analysis, the mathematical level required is high and stochastic analysis requires data such as the probabilistic distribution and the correlations of key-parameters, both of which are rarely available in general and particularly for agricultural systems. Consequently, an analysis of uncertainty is rarely done in LCA studies (Ross et al. 2002) and even less for LCAs of agricultural products.

In addition to the quantification of the uncertainty of LCA results, its reduction can be achieved by making explicit the variability in both human and natural systems if data and knowledge are available. Concerning natural system variability, the choice of the model used to convert emissions into a regional impact such as aquatic eutrophication will strongly affect the result of assessments of the environmental performance of farming systems. The integration of the cause and effect chain between emissions and impacts, and the spatial differentiation of the characterisation factors, are two means recommended by SETAC (Society of Environmental Toxicology and Chemistry) to improve the reliability of the impact assessment models (Udo de Haes et al. 1999 a and b, Potting 2000).

In a case study of pig production, the main sources of uncertainty were ranked relative to a reference LCA result by means of a sensitivity analysis. The sources of uncertainty compared were (i) the uncertainty of the reference scenario relative to the intra-system variability, (ii) the uncertainty relative to the inter-system variability of production systems (farmer practice and production mode) and (iii) the uncertainty linked to the inter-system variability of catchments as transfer compartment for nitrate in the environment (physical and climatic characteristics of catchments) (impact assessment model uncertainty).

1 Materials and Methods

1.1 Production systems

1.1.1 Production modes and farmer practice

This study dealt with the processes up to and including the production of pigs on the farm. Four contrasting production systems were defined. The Good Agricultural Practice (GAP) scenario corresponds to current intensive production (or 'conventional' production), optimised in particular with respect to fertilisation practices, as specified in the French 'Agriculture Raisonnée' standards (Rosenberg and Gallot 2002). In the GAP scenario, pigs are raised at high density in a slatted-floor confinement building. GAP is representative of an average pig production system in an agricultural region mainly producing annual field crops. The Organic Agriculture (OA) scenario corresponds to organic agriculture according to the French version of the European rules for organic animal production (Ministère de l'Agriculture et de la Pêche 2000) and the European rules for organic crop production (CEE 1991). The Red Label (RL) scenario corresponds to the Porc Fermier Label Rouge quality label (Groupements des fermiers d'Argoat 2000). In the OA and RL scenarios pigs are born and raised outdoors until weaned, and in an open-front straw-litter building at low animal density after weaning.

An Over Fertilised scenario (OF) was defined with a fertilisation exceeding crop needs (Houben and Plet 1997) for four of the major crops used as feed ingredients, leading up to a three to four-fold increase of nitrate losses for these crops. OF represents a situation which used to occur in zones of intensive animal production, such as Brittany, where manure production strongly exceeds local crop fertilisation needs.

Data concerning resource use and emissions associated with the production and delivery of inputs for crop production (fertilisers, pesticides, tractor fuel and machines) were derived according to Nemecek and Heil (2001). Data for energy carriers for road and sea transport were from the BUWAL 250 database (BUWAL 1996). Data concerning resource use and emissions associated with buildings (production and delivery of materials, construction) were from Kanyarushoki (2001). Data on crop production, transport distances, feed composition and system performance were based on statistics, estimates from experts and data from producers' associations.

For all GAP, OA and RL crops, production corresponded to good agricultural practice, i.e. fertilisation according to anticipated crop needs and integrated pest management for GAP and RL. For the four scenarios, we assumed that pig manure (liquid manure for GAP and OF, solid manure for RL, composted solid manure for OA) was used to fertilise Brittany-grown crops used as feed ingredients. For RL, GAP and OF, yield levels were averages for 1996–2000 (AGRESTE 2001, FAO 2002). The yield levels of OA crops were according to experts from the region of production. For the processes concerning the transformation of crop products into feed ingredients and the production of feed, the inventory of resources used and emissions to the environment was limited to resources and emissions associated with the use of non-renewable energy. For ingredients resulting from processes yielding more than one product (e.g. soy cake, wheat gluten), resource use and emissions were allocated according to the economic value. Data for feed production (involving, amongst others: grinding, heating, mixing, pelleting) were from van der Werf et al. (2005).

For GAP and OF, data on technical performance of the animal production stages (**Table 1**) were according to published statistics (ITP 2001). For RL, data concerning piglet production (PP) were from ITP (2001), data concerning weaning to slaughtering production (WS) were averages supplied by the RL producers' association. For OA, data on technical performance were based on an optimised model of organic pig production (Berger 2000), adjusted according to expert judgement. For GAP, OF and RL, manure was stored, while for OA, manure was composted. Overall, GAP and OF were more intensive than OA: higher feed efficiency, younger age at slaughter and less surface per pig. RL was intermediate between GAP and OA.

Table 1: Characteristics of the animal production stage for the Good Agricultural Practice, Over Fertilised, Red Label and Organic Agriculture scenarios

Scenarios	Good Agricultural Practice Over Fertilised	Red Label	Organic Agriculture
Piglet production			
Weaned piglet/sow/year	25.5	22.6	20.3
Weaning age, days	25.7	28	42
Feed per sow (boar included), kg/year	1313	1490	1695
Weaning to slaughtering			
Surface per pig, m^2	0.85	2.6	2.3
Feed to gain ratio	2.7	2.9	3.2
Slaughter age, days	175	190	195
Slaughter weight, kg	113	115	120
Feed consumed, kg	275	312	340
Total land used, m^2.year/kg of pig	5.43	6.28	9.87

Ammonia emissions due to the application of ammonium nitrate fertiliser were estimated according to ECETOC (1994) and ammonia emissions following application of slurry were estimated according to Morvan and Leterme (2001). Ammonia and nitrous oxide emissions from slurry in pig buildings were from IPCC (1996) and UNECE (1999). Methane emissions due to enteric fermentation and housing type were from IPCC (1996). For RL and OA, data on the production of excreta, emissions from buildings, during storage, during composting and from crops and paddocks, were chiefly obtained with the support of an expert panel from the Institut National de la Recherche Agronomique. The panel based its expertise on their experiments, simulation models and on their interpretation of the available literature. The emission factors thus obtained are presented in Basset-Mens and van der Werf (2005).

1.1.2 Uncertainty of the GAP scenario

In order to explore the robustness of the GAP results, an uncertainty analysis was conducted using scenario analysis. Crop yields, WS feed to gain ratio, field emissions (NH_3, N_2O and NO_3) and emissions of NH_3 and N_2O from buildings and manure storage were identified as important issues for the uncertainty of results. For the parameters concerning these issues, a high and a low value reflecting what we coined 'realistic' rather than overall uncertainty were defined, in addition to the default reference value. The 'realistic' uncertainty interval thus defined contains about two thirds of the overall uncertainty (assuming a normal distribution) for the parameter concerned (Basset-Mens and van der Werf 2005). In order to assess the relative importance of each of the four issues, we constructed favourable and unfavourable variants for each issue by combining all favourable values, on the one hand, and all unfavourable values, on the other hand. The summation of the uncertainty sources quantified is proposed as an indicator of the uncertainty of the GAP results. The details about this scenario-based uncertainty analysis are given in Basset-Mens and van der Werf (2005). Finally, in order to assess the influence of the choice of functional unit, impacts were expressed by two functional units corresponding to the two main functions of agricultural production systems. Kg of pig produced (live weight at slaughter) reflects its function as a producer of market goods, whereas ha of land used reflects its function as a producer of non-market goods (e.g. environmental services).

1.2 Natural systems

The natural context was considered for the transfer of nitrate in catchments through hydrological behaviour and rainfall. Three contrasting catchment types were selected (**Table 2**). Although they do not represent the entire range of variation observed in Brittany, these catchments exhibit a large range of variation with respect to the fraction of riparian zone area, with respect to patterns of flow dynamics and nitrate concentration. The catchments representing these types have been monitored in detail for at least 5 years.

Three levels of effective rainfall (resulting runoff of the rain falling on a catchment) were selected : 300, 435 and 700 mm. Thus, nine catchment scenarios were obtained by combining the three catchment types and the three levels of effective rainfall. These catchment scenarios are described in Basset-Mens et al. (submitted).

Table 2: Characteristics of the catchment types

	Geology	Wetlands (% of total surface)	Seasonal cycle
Type P (Pouliou)	Granite	High (25%)	Reversed*
Type K (Kervidy)	Schist	Middle (14%)	Normal*
Type S (Stang Cau)	Granite	Low (5%)	Normal*

* Normal cycles present high nitrate concentration in winter and low in summer and conversely for reversed cycles.

1.3 Evaluation methodology

1.3.1 Current LCA

The current LCA methodology was applied for seven impact categories. Only results for eutrophication, climate change and acidification are presented in this article, as these impacts are affected by all of the studied key-parameters, while the remaining impact categories were sensitive only to technical parameters. As recommended by Guinée et al. (2002), Eutrophication Potential (EP) was calculated using the generic EP factors in kg PO_4-eq., Global Warming Potential for a 100 year time horizon (GWP_{100}) was calculated according to the GWP_{100} factors by IPCC (Houghton et al. 1996) in kg CO_2-eq. and Acidification Potential (AP) was calculated using the average European AP factors by Huijbregts (1999) in kg SO_2-eq.

1.3.2 Eutrophication

Assessing the fate factor for nitrate in catchments (the ratio of annual fluxes of N export from the catchment in the river over annual fluxes of N input in the catchment, namely leachable nitrate) requires the quantification of the N retention capacity of the catchment, which is generally thought to be due to heterotrophic denitrification in the upper horizon of bottom land (Sebilo et al. 2003). This was done using the hydrology and biogeochemistry model INCA (Integrated Nitrogen in Catchments) (Whitehead et al. 1998, Wade et al. 2002). INCA is a semi-distributed and process-based model simulating the nitrogen fate through terrestrial systems and rivers. The main components of INCA as described in Whitehead et al. (1998) and Wade et al. (2002) consist of:

- The hydrological model that calculates the flow of hydrologically effective rainfall in three compartments: the reactive (soil) and groundwater zones of the catchment and the river reach. Surface and subsurface pathways are mixed into the river in the proportions defined by the baseflow index (BFI). The BFI represents the proportion of water being transferred to the lower groundwater zone. Each compartment is characterised by its residence time. This component of the model drives N fluxes through the catchment.
- The catchment nitrogen process model that simulates N transformations in the soil and groundwater of the catchment. This component includes plant uptake and microbial processes such as mineralisation, nitrification, denitrification.
- The river nitrogen process model that simulates dilution and in-stream N transformations and losses such as nitrification and denitrification. As shown by Durand (2005), it is possible to consider wetlands as part of this component.

Residence time, BFI and biochemical reaction parameters are defined by calibration. All the equations are of the first order.

The model was calibrated against flow and chemistry data from the selected catchments. For the simulation of nitrate transport and the calculation of fate factors, estimated values for leachable nitrate based on historical fertilisation data were used. Leachable nitrate increased from 3.7 NO_3-N kg ha^{-1} (1965) to 93 NO_3-N kg ha^{-1} (2003), and it remained stable afterwards during several decades prospecting the future. This stabilisation of the nitrogen load allowed the model to reach an equilibrium state and to estimate the real fate factor for nitrate, eliminating the long term storage or release effect. The catchment nitrogen process model was by-passed and leachable nitrate, as defined in the historical trajectories, was directly injected into the soil. The in-stream process model was used to estimate the denitrification process in the stream and the wetland zone. Then the nitrate concentrations in the three catchments were set to zero and historical loads were applied as N input over time. The evolution of the nitrogen output in the river for each scenario was then simulated. The evolution over the entire simulation period of the nitrate fate factor was calculated for each catchment scenario. The fate factor used in the LCA was obtained after stabilisation at the final steady state (as a consequence of the stabilisation of the nitrogen load inputs).

The fate factor of the scenarios ranged from 0.9 (low percentage wetlands, high effective rainfall) to 0.4 (high percentage wetlands, low effective rainfall). These fate factors were used to assess the eutrophication impact of the GAP scenario by multiplying them with the generic EP factors. The details of this approach are in Basset-Mens et al. (submitted).

1.4 Reference result

All the results were referred to a reference LCA result obtained by combining a production mode (conventional production mode), a level of farmer practice (good agricultural practice = GAP scenario), with average values for key parameters and the standard evaluation methodology, including aquatic eutrophication (fate factor for nitrate = 1).

2 Results

In this presentation of results, we will refer to both results expressed per ha and per kg of pig produced. However, in **Figs. 1** and **2**, only the results expressed per kg of pig produced are shown. Per kg of pig, the reference result for eutrophication is 0.0208 kg PO_4-eq, while per ha it is 38.3 kg PO4-eq (**Table 3**). Both per kg and per ha, uncertainty of the GAP scenario is large (around ±50%) and is mainly due to field emissions (around ± 35%) (see Fig. 1). Both per kg and per ha, eutrophication is lower for RL (–20% and –30%,

Table 3: The environmental impacts of the GAP scenario of pig production expressed per kg of pig and per hectare for eutrophication, climate change and acidification

Impact category	Per kg of pig	Per hectare
Eutrophication (kg PO_4-eq)	0.0208	38.3
Climate change (kg CO_2-eq)	2.30	4236
Acidification (kg SO_2-eq)	0.0435	80.1

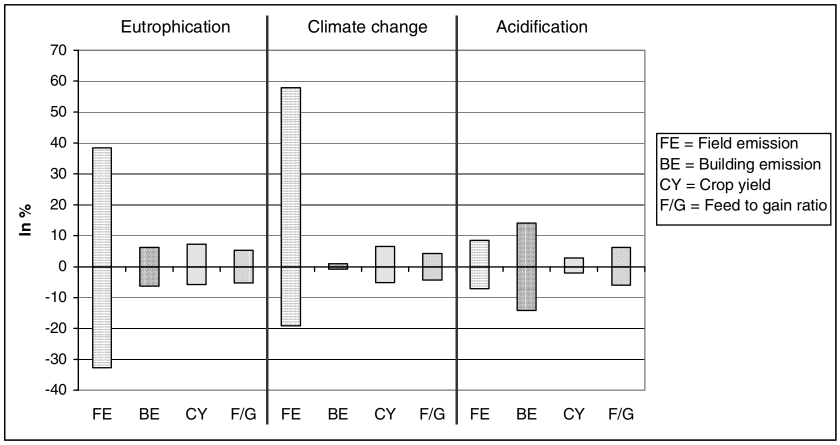

Fig. 1: Contribution of the uncertainty of field emissions (FE), building and manure emissions (BE), crop yield (CY) and feed to gain ratio (F/G) to the overall uncertainty for eutrophication, climate change and acidification per kg of pig produced for the GAP scenario

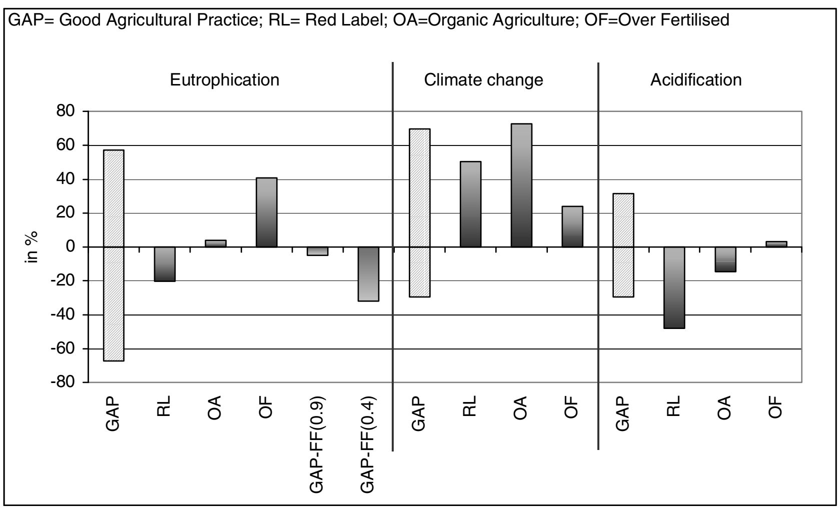

Fig. 2 : Uncertainty of LCA results (per kg of pig) for eutrophication, climate change and acidification. Uncertainty for GAP corresponds to uncertainty due to the intra-system variability (uncertainty of technical parameters and emissions factors, see Fig. 1). Other bars indicate differences relative to the reference result for the RL, OA and OF scenarios and when using 0.9 and 0.4 instead of 1 for the fate factor

respectively) (see Fig. 2). For OA, the result is very dependent on the choice of the FU: eutrophication is similar per kg, but 40% less per ha. Eutrophication is 40% higher for OF than for the reference. Finally, when the fate factor is 0.9 or 0.4, instead of 1, the eutrophication result is reduced by 5 to 32% (see Fig. 2).

The reference result for climate change is 2.30 kg CO_2-eq per kg of pig and 4236 kg CO_2-eq per ha. Both per kg and per ha, uncertainty intervals of the GAP scenario are very large and are mainly due to field emissions. Both per kg and per ha, climate change is higher for RL (+50% and +30%, respectively). As for eutrophication, the climate change result for OA is very dependent on the FU: climate change is 70% higher per kg, but is similar per ha. Finally, OF results in an increase of more than 20% of the climate change impact relative to the reference result, because in the calculation of N_2O emissions (Mosier et al. 1998), indirect emissions of N_2O are assumed to be 2.5% of the nitrate leaching, which increases significantly in the OF scenario.

Per kg of pig, the reference result for acidification is 0.0435 kg SO_2-eq, while per ha it is 80.1 kg SO_2-eq (see Table 3). Both on a per kg and a per ha basis, uncertainty intervals of the GAP scenario for acidification are smaller than for eutrophication and climate change (± 30% and ± 20%, respectively). Uncertainty is mainly due to building emissions and secondarily to field emissions (see Fig. 1). Both per kg and per ha, acidification is much smaller for RL: 48% less per kg and 55% less per ha. The difference between the reference result and OA once more depends on the FU: acidification results are close when expressed per kg (15% less for OA) (see Fig. 2), while per ha, acidification is 53% less for OA. Finally, the OF scenario is similar to the reference result for acidification (see Fig. 2).

3 Discussion and Conclusion

Among the parameters tested for their sensitivity on the reference result, uncertainty of the production scenario GAP (intra-system variability) which has been studied in details was large: around ±50% for eutrophication, –30% to +70% for climate change and around ±30% for acidification. It originated primarily from the estimation of emission factors at the inventory stage. For eutrophication and climate

change, field emissions were the main source of uncertainty, while for acidification it was building emissions. As interactions between key emissions were not fully integrated, the estimation of the uncertainty of GAP result can be considered more as extreme than as realistic.

The uncertainty of the results can reflect a known variability of the processes involved at the scale of the study: for instance nitrate leaching is a function of soil characteristics and climate, but uncertainty can also arise from a lack of knowledge about these processes. Namely, for the emission of N_2O in the field due to nitrogen input, we used the emission factor and the uncertainty interval proposed by Mosier et al. (1998) (Basset-Mens and van der Werf 2005), which are based on a literature review of field studies conducted in temperate regions of the world, with different fertiliser types, soils and climates. The large uncertainty range reflects the contrasting background conditions of the measurements. An approach is required, for instance for the use of a suitable simulation model, which would allow a more reliable estimation of emission factors (for N_2O, but also for NO_3 and NH_3) by assigning this variation to its controlling variables in order to produce an estimate that takes into account both environmental conditions (climate, soil…), farmer practices and technology used.

A practical methodology was defined to analyse the uncertainty of the reference scenario results. It could also be interesting to perform this uncertainty analysis using Monte Carlo simulations, but this would imply making assumptions about the probabilistic distribution of each key-parameter.

We explored the inter-system variability. The difference between RL and OF, on the one hand, and GAP, on the other, did not depend much on the FU used, because these systems present similar degrees of intensification, whereas the difference between OA and GAP was very dependent on the FU. For production systems with contrasting goals such as GAP and OA, the use of these different FU is very important.

For eutrophication, the difference between GAP and OF was larger than the difference between GAP and the other two systems (RL and OA). This result illustrates that farmer practices may affect the final result more than production modes.

RL and OA scenarios did better than or similar to GAP for eutrophication and acidification, but they did worse for climate change. Eutrophication and acidification are considered as hot spots for the GAP scenario and even more for the OF scenario. However, this study reveals climate change as a hot spot for RL and OA. Basset-Mens and van der Werf (2005) have demonstrated that the straw litter housing system was mainly responsible for this hot spot, but also that this production stage seems to present important margins of improvement in this respect.

For eutrophication, the consequence of integrating the different catchment types in the analysis has been considered. Contrasting fate factors for nitrate were obtained by simulating nitrate transfer in nine catchment scenarios with the INCA simulation model. These fate factors ranged from 0.4 to 0.9, revealing potentially diverse and important N retention capacities for the catchments depending on their hydrology, the effective rainfall and the wetland surface. These first simulations illustrate the importance of taking into account the environment where the pollutants are transferred in assessing aquatic eutrophication. These results complete the work of Huijbregts and Seppälä (2000, 2001) and demonstrate the need for further research on the simulation of the fate of pollutants in LCA models. They furthermore reveal a wide margin of improvement for assessing the aquatic eutrophication impact.

In conclusion, in this study, an important part of the variability of the human system (production mode, practice) and of the natural system (catchment type) was made explicit, which allowed a reduction of the uncertainty of the LCA results. Two major issues were also identified for further reduction of the uncertainty of the final results: a better knowledge and modelling of field and building emissions in agricultural systems and the conception of more reliable impact assessment models for regional impacts such as aquatic eutrophication.

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